

Magnon softening and damping in the ferromagnetic manganites due to orbital correlations

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Abstract

We present a theory for spin excitations in ferromagnetic metallic manganites and demonstrate that orbital fluctuations have strong effects on the magnon dynamics in the case these compounds are close to a transition to an orbital ordered state. In particular we show that the scattering of the spin excitations by low-lying orbital modes with cubic symmetry causes both the magnon softening and damping observed experimentally.

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Metallic ferromagnetic manganites belong to the class of double exchange systems, in which the motion of doped charge carriers establishes a ferromagnetic interaction between neighboring Mn spins. In some of the colossal magnetoresistive manganese perovskites, the spectrum of magnetic excitations (magnons) has a rather unusual shape: while showing standard Heisenberg behavior at small momenta the magnon dispersion exhibits a pronounced softening near the Brillouin zone boundary. In addition, magnons with short wave lengths cease to be well defined quasiparticles because width of their spectral density peaks become comparable with their energy at the Brillouin zone boundary. [1,2,3] Theoretically, Furukawa [4] has

explained this observation by the scattering of the magnons due to the optical phonons. Khaliullin and Kilian [5] attributed the effect to the orbital fluctuations.

The effective Hamiltonian of scattering of the magnons b_i by the orbital excitations of the e_g electrons, expressed by $f_{i\alpha}$ -fermions has the form [5]:

$$H = - \sum_{\langle i,j \rangle_\gamma} \sum_{\alpha\beta} x t_\gamma^{\alpha\beta} f_{i\alpha}^\dagger f_{j\beta} [1 - \frac{1}{4S} (b_i^\dagger b_i + b_j^\dagger b_j - 2b_i^\dagger b_j)]. \quad (1)$$

In the present work, we introduce also a direct effective interaction between the e_g orbitals of the nearest-neighbor (NN) manganese sites

$$H_{orb} = V \sum_{\langle ij \rangle_\gamma} \tau_i^{(\gamma)} \tau_j^{(\gamma)}, \quad (2)$$

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where the orbital isospins defined as $\tau^{(z)} = \sigma^z/2$, $\tau^{(x/y)} = -(\sigma^z \pm \sqrt{3}\sigma^x)/4$, and σ^z and σ^x are Pauli operators acting in the orbital sector. In the classical limit, the Hamiltonian (2) can be diagonalized in the reciprocal space giving two normal modes $\sigma_{\mathbf{q}}^{(+)}$ and $\sigma_{\mathbf{q}}^{(-)}$, with dispersion relations

$$\omega_{\mathbf{q}}^{\pm} = \omega_0 \left(1 + (\gamma_{\mathbf{q}} \pm \sqrt{\eta_2^2 \mathbf{q} + \eta_3^2 \mathbf{q}}) \text{sign}(V) \right), \quad (3)$$

where $\omega_0 = 3|V|/8$, $\eta_{\mathbf{q}}^{(2)} = \sqrt{3}(c_y - c_x)/6$, $\eta_{\mathbf{q}}^{(3)} = (2c_z - c_x - c_y)/6$ and $\gamma_{\mathbf{p}} = (c_x + c_y + c_z)/3$.

An effective Hamiltonian describing the interaction between the magnons and the low-lying collective orbital mode can be derived by combining the spin-orbital coupling in Eq.(1) with the direct orbital-coupling term (2), leading to

$$H_{s-orb} = \sum_{\mathbf{p}\mathbf{q}} \left(g_{\mathbf{p}\mathbf{q}}^+ \sigma_{-\mathbf{q}}^{(+)} + g_{\mathbf{p}\mathbf{q}}^- \sigma_{-\mathbf{q}}^{(-)} \right) b_{\mathbf{p}}^{\dagger} b_{\mathbf{p}+\mathbf{q}}. \quad (4)$$

The magnon spectrum is given by $\tilde{\omega}_{\mathbf{p}} = \omega_{\mathbf{p}} + \text{Re}[\Sigma(\omega_{\mathbf{p}}, \mathbf{p})]$ with the mean-field dispersion $\omega_{\mathbf{p}} = zD(1 - \gamma_{\mathbf{p}})$ (resulting from $\langle f_{i\alpha}^{\dagger} f_{j\beta} \rangle$ [5]). $\Sigma(\omega, \mathbf{p})$ denotes the magnon self-energy, where $\tilde{\Gamma}_{\mathbf{p}} = -\text{Im}[\Sigma(\omega_{\mathbf{p}}, \mathbf{p})]$ is the magnon damping. The magnon self-energy is the sum of two contributions, stemming from orbiton particle-hole excitations and from the orbital collective mode.

Calculated magnon dispersions are displayed in Figs. 1 and 2. The inset of Fig. 1 shows the momentum dependence of magnon width. Scattering of the magnons due to the excitations of the orbiton particle-hole pairs does not change the Heisenberg type of the spin-wave dispersion (it results only in a partial decrease of their bandwidth [dotted lines on Figs. 1 and 2]). On contrary, the development of the soft orbital modes affects the spin dynamics substantially. Their effect is particularly pronounced for the spin excitations with momentum \mathbf{p} along the direction $(0, 0, \xi)$, where the magnon dispersion flattens as one approaches the Brillouin zone boundary. At the same time, the magnon width increases abruptly (see inset in Fig. 1). The effect of the collective modes is small for the direction (ξ, ξ, ξ) (see Fig. 2). This anisotropic behavior originates from the peculiar structure of the dispersion in Eq. (3), exhibiting soft lines in direction $(0, 0, \pi)$ and equivalent ones.

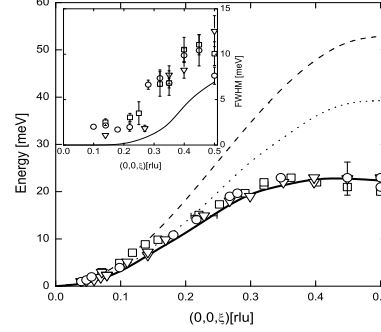


Fig. 1. Magnon dispersion along the $(0, 0, \xi)$ -direction. The dashed line corresponds to the function $\omega_{\mathbf{p}}$. The solid (dotted) line gives $\tilde{\omega}_{\mathbf{p}}$ with (without) contribution from the orbital collective mode. Inset: Magnon width $2\tilde{\Gamma}_{\mathbf{p}}$. Here squares, triangles and circles give experimental data [1] for $\text{Pr}_{0.63}\text{Sr}_{0.37}\text{MnO}_3$, $\text{Nd}_{0.7}\text{Sr}_{0.3}\text{MnO}_3$, and $\text{La}_{0.7}\text{Ca}_{0.3}\text{MnO}_3$, respectively.

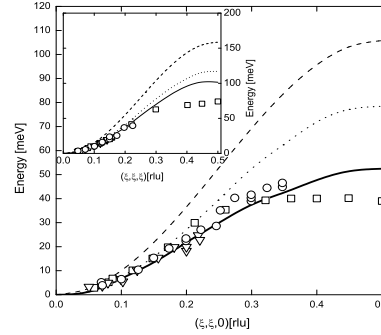


Fig. 2. Magnon dispersion along the $(\xi, \xi, 0)$ - $[(\xi, \xi, \xi)]$ -direction [inset]. Line styles are the same as in Fig. 1. Experimental data in main figure is taken from [1]. The Pr- (Nd-, La-) data shown in the inset is taken from [3] ([2]).

To summarize, a strong damping of the short wave length magnons and a marked deviation of their spectrum from a canonical Heisenberg form may originate from the scattering of the magnons by a collective orbital mode, and therefore can be understood as a precursor effect of orbital ordering.

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